

## Probing the Majorana Nature and CP Properties of Neutralinos

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Two powerful and straightforward methods are presented for probing the Majorana nature and CP violation of neutralinos at future  $e^+e^-$  linear colliders.

The search for supersymmetry (SUSY) is one of the main goals at present and future colliders as SUSY is generally accepted as one of the most promising concepts for physics beyond the Standard Model [1]. A characteristic feature of SUSY theories is the presence of neutralinos  $\tilde{\chi}^0$ , the spin-1/2 Majorana superpartners of the neutral gauge and Higgs bosons. The neutralinos are expected to be among the light supersymmetric particles that can be produced copiously at future high-energy colliders. Once several neutralino candidates are observed at such high-energy collider experiments it will be crucial to establish the Majorana nature and CP properties of neutralinos as well as to reconstruct the fundamental SUSY parameters [2].

In this report, we present two powerful and straightforward methods for probing the Majorana nature and CP violation in the neutralino system in the framework of the minimal supersymmetric standard model (MSSM). One method is based on a combined analysis of the threshold excitations of neutralino pair production in  $e^+e^-$  annihilation and the fermion invariant mass distribution near the end point of three-body neutralino fermionic decays [3,4]. The other method is based on the measurement of  $Z$ -boson polarization in the two-body decays  $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z$  [5].

The mixing of the neutral U(1) and SU(2) gauginos,  $\tilde{B}$  and  $\tilde{W}^3$ , and higgsinos,  $\tilde{H}_{1,2}^0$ , in the MSSM is described by a  $4 \times 4$  matrix  $N$ , diagonalizing the  $4 \times 4$  symmetric mass matrix. The relevant fundamental SUSY parameters are the U(1) and SU(2) gaugino mass parameters,  $M_1$  and  $M_2$ , the higgsino mass parameter  $\mu$  and  $\tan\beta = v_2/v_1$ , the ratio of the two Higgs vacuum expectation values. In general the mass parameters  $M_1$ ,  $M_2$  and  $\mu$  are complex. By re-parameterizing the fields,  $M_2$  can be taken real and positive, while the parameter  $M_1$  is assigned the phase  $\Phi_1$  and the parameter  $\mu$  the phase  $\Phi_\mu$ . For the phases different from 0 and  $\pi$  the neutralino system is CP noninvariant.

When the electron and fermion masses are neglected both the production processes,  $e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$ , near threshold and the three-body decays,  $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 f \bar{f}$  near the fermion invariant mass end point are effectively regarded as processes of a static vector or axial-vector current exchange between two

neutralinos. In the CP invariant case, the production of a neutralino  $\{ij\}$  pair and the neutralino decay  $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 V$  through a vector or axial-vector current with positive intrinsic CP parity satisfy the CP relations

$$1 = +\eta^i \eta^j (-1)^L \quad (1)$$

$$1 = -\eta^i \eta^j (-1)^L \quad (2)$$

in the static limit of two neutralinos, where  $\eta^i = \pm i$  is the intrinsic CP parity of  $\tilde{\chi}_i^0$  and  $L$  is the orbital angular momentum of the produced neutralino  $\{ij\}$  pair and of the final state of  $\tilde{\chi}_j^0$  and  $V$ , respectively. The selection rules (1, 2) reflect that if two neutralinos  $\tilde{\chi}_i^0$  and  $\tilde{\chi}_j^0$  have the same or opposite CP parity, the current for the neutralino pair production must be pure axial-vector or pure vector form, respectively. The intrinsic sign difference of the two selection rules is because two  $u$ -spinors are associated with the currents in the neutralino to neutralino transition, while a  $u$  spinor and a  $v$  spinor are involved in the neutralino pair production.

One immediate consequence of the selection rules (1,2) is that, in the CP invariant case, if the production of a pair of neutralinos with the same (opposite) CP parity through a vector or axial-vector current is excited slowly in  $P$  waves (steeply in  $S$  waves), then the neutralino to neutralino transition via such a vector or axial-vector current is excited sharply in  $S$  waves (slowly in  $P$  waves). In the CP noninvariant case the orbital angular momentum is, however, no longer restricted by the selection rules. Consequently, CP violation in the neutralino system can clearly be signalled in two ways by (a) the sharp  $S$ -wave excitations of the production of three non-diagonal  $\{ij\}$ ,  $\{ik\}$  and  $\{jk\}$  pairs near threshold [2,3] or by (b) the simultaneous  $S$ -wave excitations of the production of any non-diagonal  $\{ij\}$  pair in  $e^+e^-$  annihilation near threshold and of the fermion invariant mass distribution of the neutralino three-body decays  $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 f \bar{f}$  near the kinematical end point [4]. It is in particular a great merit that even if only the two light neutralinos  $\tilde{\chi}_{1,2}^0$  are accessed kinematically at the initial-phase  $e^+e^-$  linear collider, the combined analysis of the production of the neutralino  $\{12\}$  pair and the decay  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 f \bar{f}$  allows us to probe CP violation in the neutralino system. A clear numerical demonstration of the combined analysis of the processes,  $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$  and  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 l^+ l^-$ , is illustrated in Fig.1 for the parameter set  $\{\tan \beta = 10, |M_1| = 100 \text{ GeV}, M_2 = 150 \text{ GeV}, |\mu| = 400 \text{ GeV}, \Phi_\mu = 0; m_{\tilde{L},R} = 250/200 \text{ GeV}\}$ .

Once two-body decays of a neutralino  $\tilde{\chi}_i^0$  into  $Z$ , Higgs bosons or sfermions are kinematically open, the combined production-decay analysis cannot be exploited for probing CP violation in the neutralino system. Nevertheless, if the two-body decays  $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z$  is not too strongly suppressed, the  $Z$  polariza-

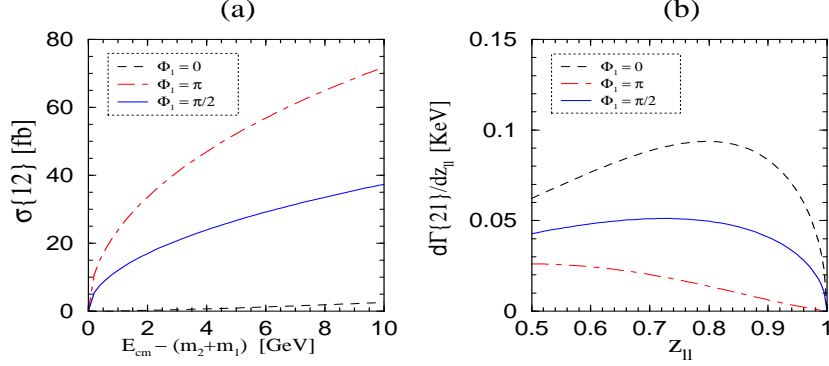


Figure 1: (a) The threshold behavior of the neutralino production cross section  $\sigma\{12\}$  and (b) the lepton invariant mass distribution for the parameter set given in the text.

tion reconstructed via leptonic  $Z$ -boson decays with great precision allows us to probe the Majorana nature and CP violation in the neutralino system [5]. The Majorana nature of neutralinos forces the vector and axial vector  $Z\tilde{\chi}^0\tilde{\chi}^0$  couplings to be pure imaginary and pure real, respectively. This characteristic Majorana property leads to one important relation between the decay widths with the  $Z$ -boson helicities  $\pm 1$ :  $\Gamma[\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z(+)] = \Gamma[\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z(-)]$ , that is valid even in the CP noninvariant case. In addition, CP violation in the neutralino system can be probed by measuring the ratio of the longitudinal to transverse decay widths, if the relevant neutralino masses are measured with good precision, independently of the decay modes.

The suggested methods can be exploited experimentally in a straightforward manner so that they are expected to provide us with first-stage indications of the Majorana nature and CP violation in the neutralino system.

## References

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